Decelerating Flows in TeV Blazars: A Resolution to the BL Lac – FR I Unification Problem

Markos Georganopoulos[1] & Demosthenes Kazanas[2]

Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771, USA.

ABSTRACT

TeV emission from BL Lacertae (BL) objects is commonly modeled as Synchrotron-Self Compton (SSC) radiation from relativistically moving homogeneous plasma blobs. In the context of these models, the blob Lorentz factors needed to reproduce the corrected for absorption by the diffuse IR background (DIRB) TeV emission are large ($\delta \gtrsim 50$). The main reason for this is that stronger beaming eases the problem of the lack of $\sim$ IR-UV synchrotron seed photons needed to produce the de-absorbed $\sim$ few TeV peak of the spectral energy distribution (SED). However, such high Doppler factors are in strong disagreement with the unified scheme, according to which BLs are FR I radio galaxies with their jets closely aligned to the line of sight. Here, motivated by the detection of sub-luminal velocities in the sub-pc scale jets of the best studied TeV blazars, MKN 421 and MKN 501, we examine the possibility that the relativistic flows in the TeV BLs decelerate. In this case, the problem of the missing seed photons is solved because of Upstream Compton (UC) scattering, a process in which the upstream energetic electrons from the fast base of the flow 'see' the synchrotron seed photons produced in the slow part of the flow relativistically beamed. Modest Lorentz factors ($\Gamma \sim 15$), decelerating down to values compatible with the recent radio interferometric observations, reproduce the $\sim$ few TeV peak energy of these sources. Furthermore, such decelerating flows are shown to be in agreement with the BL - FR I unification, naturally reproducing the observed BL/FR I broad band luminosity ratios.

Subject headings: galaxies: active — quasars: general — radiation mechanisms: nonthermal — X-rays: galaxies

[1]Also NAS/NRC Research Associate; email: markos@milkyway.gsfc.nasa.gov

[2]email: Demos.Kazanas-1@nasa.gov

1. Introduction

There is a small but growing family of blazars detected at TeV energies. These belong exclusively to the class of high peak frequency BLs, i.e. blazars whose synchrotron component peaks at X-ray energies. TeV emitting BLs are of particular interest because of the possibility of absorption of their TeV emission by the DIRB (Nikisov 1962; Gould & Schréder 1966; Stecker, de Jager & Salamon 1992). Study of their spectra in the TeV range can be used to probe the properties of DIRB as a function of redshift z (Salamon and Stecker 1998), given that the magnitude of absorption depends on the redshift of the source and the, still elusive, DIRB spectrum (Malkan & Stecker 2001; Primack et al. 2001; Aharonian et al. 2002).

The absorption of the TeV photons of this blazar class suggests that both the intrinsic peak photon energy E_p and peak luminosity L_p of the high energy (TeV) component are higher than those observed. Even for the nearby ($z = 0.031$) MKN 421, E_p can increase by a factor of ~ 10 after de-absorption to $\sim 5 - 10$ TeV (de Jager & Stecker 2002). The de-absorbed spectrum of H1426+428 at z=0.129 is even more extreme, characterized by $E_p \gtrsim 10$ TeV (Aharonian et al. 2002). Modeling of these sources has been done in the framework of the homogeneous SSC model [e.g. Coppi (1992); Mastichiadis & Kirk (1997)], according to which a blob of energetic plasma is moving with a constant Lorentz factor Γ forming a small angle θ to the line of sight. Such models require high Doppler factors ($\delta = 1/\Gamma(1 - \beta\cos\theta) \gtrsim 50$, where β is the dimensionless speed of the flow and θ its angle to the observer's line of sight) to reproduce the de-absorbed E_p [e.g. Krawczynski, Coppi & Aharonian (2002); see also next section]. However, even smaller values of $\delta(\simeq 10)$ are in conflict (Chiaberge et al. 2000) with the unification scheme according to which BLs represent FR I radio galaxies viewed at small $\theta\,(\simeq 1/\Gamma)$ (Urry & Padovani 1995). Also, these high values of δ are in disagreement with the small values of the apparent velocities observed in the sub-pc regions of the TeV BL Mkn 421 and Mkn 501 (e.g. Marscher (1999)). In this note we propose that the above issues can be resolved by postulating that the TeV blazar emission originates in a relativistic but *decelerating* flow. In §2 we present a quantitative analysis and formulation of the above arguments, while in §3 we outline the basic notions behind our proposal and explain why and how they resolve the outstanding issues discussed in §2. Finally, in §4 we discuss some further issues.

2. Problems with Uniform Velocity TeV Blazar Models

The Blazar Spectra: One of the characteristics of the synchrotron components of the TeV blazar spectra is a break at an energy $\epsilon_b \sim 10^{-4} - 10^{-6}$ (unprimed energies are in the observer frame while primed ones in the flow rest frame, all normalized to the rest

mass of the electron $m_e c^2$), with most of the (comoving) synchrotron energy density above ϵ'_b, a feature that significantly affects their TeV emission: Because of the reduction in the inverse Compton (IC) scattering cross section in the K-N regime and the break in the photon energy density at $\epsilon' < \epsilon'_b$, electrons with energies $\gamma \gtrsim 1/\epsilon'_b$ will channel a decreasing fraction of their energy to IC scattering, leading to a peak in the IC luminosity at $\epsilon'_p \simeq 1/\epsilon'_b$ even if the maximum electron energy is $\gamma_{max} \gg 1/\epsilon'_b$. For a source moving with a Doppler factor δ relative to the observer ϵ'_b and ϵ'_p will be $\epsilon_b = \delta\epsilon'_b$ and $\epsilon_p = \delta\epsilon'_p$ yielding

$$\delta^2(\epsilon'_b\,\epsilon'_p) \simeq (\epsilon_b\,\epsilon_p) \quad \text{or} \quad \delta \simeq (\epsilon_b\,\epsilon_p)^{1/2} = 40\;(\nu_{b,16}\;E_{p,\,10\,\mathrm{TeV}})^{1/2}, \tag{1}$$

where $\nu_{b,16}$ is the *observed* synchrotron break frequency in units of 10^{16} Hz and $E_{p,\,10\,\mathrm{TeV}}$ is the energy of the *de-absorbed* IC peak in units of 10 TeV. De-absorbed E_p values in excess of 10 TeV then imply relativistic flows in blazars with $\Gamma \gtrsim 40$. The crucial point in the above argument, namely that the IC luminosity peaks at $\epsilon'_p \lesssim 1/\epsilon'_b$, can be demonstrated explicitly within the homogeneous SSC models: Assume, as customary, continuous injection of a power law electron distribution within a uniform source at a rate $Q(\gamma) \propto \gamma^{-s}$, $\gamma \le \gamma_{max}$. The steady state electron distribution is then

$$n(\gamma) \propto \begin{cases} \gamma^{-s} & \text{for } \gamma < \gamma_b \\ \gamma^{-(s+1)} & \text{for } \gamma_b \le \gamma \le \gamma_{max}, \end{cases} \tag{2}$$

with γ_b the electron energy below which electrons escape from the source faster than they radiatively cool. The corresponding comoving synchrotron energy density distribution is

$$u(\epsilon') \propto \begin{cases} \epsilon'^{-(s-1)/2} & \text{for } \epsilon' < \epsilon'_b \\ \epsilon'^{-s/2} & \text{for } \epsilon'_b \le \epsilon \le \epsilon'_{max}, \end{cases} \tag{3}$$

where $\epsilon'_b = b\gamma_b^2$, $\epsilon'_{max} = b\gamma_{max}^2$, and b is the comoving magnetic field in units of its critical value $B_c = m_e^2 c^3/e\hbar = 4.4 \times 10^{13}$ G. Fits to the synchrotron spectra of TeV blazars require $1 < s < 2$, with comoving peak synchrotron luminosity at ϵ'_{max}. We now examine the energy ϵ'_p at which the IC luminosity peaks as a function of the maximum electron energy γ_{max}. The K-N influence on the cross section begins at $\gamma_{max} \simeq 1/\epsilon'_{max}$. Above that energy the electrons interact only with the fraction of the synchrotron spectrum at energies less than $\epsilon' \lesssim 1/\gamma$, while the maximum photon energy resulting from the IC is $\epsilon'_M \approx \gamma_{max}$. If $L(\epsilon'_M)$ is the photon scattering rate to energy ϵ'_M, the IC luminosity at this energy is

$$\epsilon'_M L(\epsilon'_M) \propto \epsilon'_M\; n(\gamma_{max})\; \epsilon' u(\epsilon')\; \gamma_{max}^2. \tag{4}$$

Setting $\epsilon' = 1/\gamma_{max}$ as the appropriate seed photons (photons of larger energy are in the K-N regime, and photons of lower energy give lower ϵ'_{IC}), and using eq. (2), (3) we obtain

$$\epsilon'_M L(\epsilon'_M) \propto \begin{cases} \epsilon_M'^{(2-s)/2} & \text{for } \epsilon'_M \lesssim 1/\epsilon'_b \\ \\ \epsilon_M'^{(1-s)/2} & \text{for } \epsilon'_M \gtrsim 1/\epsilon'_b \end{cases} \tag{5}$$

where we have also used $\epsilon'_M = \gamma_{max}$. Therefore, for $1 < s < 2$ the luminosity at maximum photon energy $\epsilon'_M L(\epsilon'_M)$ increases with γ_{max} for $\epsilon'_M = \gamma_{max} \lesssim 1/\epsilon'_b$ and decreases for $\epsilon'_M \gtrsim 1/\epsilon'_b$, achieving its peak luminosity at energy $\epsilon'_p \approx 1/\epsilon'_b$.

Blazar Unification: According to the unification scheme of radio loud active galaxies (e.g. Urry & Padovani 1995) BLs are FR I radio galaxies with their jets oriented close to the line of sight. The average Lorentz factor Γ of the jet flows, derived by matching the luminosity functions of BL and FR I samples, were estimated to be $\Gamma \sim 3 - 5$ (Urry & Padovani 1991; Hardcastle et al. 2003), in clear disagreement with the values of the Doppler factors required by the homogeneous SSC models for the TeV blazars. The high Doppler factors estimated on the basis of homogeneous SSC models imply that for $\Gamma \simeq \delta \simeq 50$, $\theta \approx 1/\Gamma \approx 1^\circ$ requiring sources very well aligned to the line of sight, thus grossly overpredicting the number of FR I galaxies above a given limiting flux (this actually would be the case even with the much smaller value of $\Gamma \simeq 10$; Hardcastle et al. (2003)).

In a different aspect of the same problem, Chiaberge et al. (2000) showed that the FR I nuclei are overluminous by a factor of $10 - 10^4$ compared to their luminosity should they have been misaligned BLs harboring flows with Lorentz factors $\Gamma \sim 15$. Applying to sub-pc scales the arguments of Laing et al. (1999) concerning the structure of FR I kpc scale jets, they opted for jets with a high Γ 'spine' surrounded by lower Γ sheath. For a source at a small angle to the line of sight the emission is dominated by the fast spine, while, at large angles this radiation is beamed out of the observer's direction and the observed spectrum is dominated by the mildly beamed emission by the slower sheath.

However, recent VLBA (Marscher 1999), VLBI (Edwards & Piner 2002), and combined VSOP and VLBI (Piner et al. 1999) studies do not detect any high velocity components in the jets of the two TeV sources MKN 421 and MKN 501. These observations are compatible with subluminal ($\beta_{app} \sim 0.3 - 0.6$, Piner et al. 1999, Edwards et al. 2002) or mildly relativistic ($\beta_{app} \sim 2$, Marscher 1999) sub-pc velocities. A value of $\delta \sim 50$, as needed in modeling the TeV emission of these sources, could produce the observed velocities only for $\theta \lesssim 0.1^\circ$. Rather than assuming such an extraordinary jet alignment for both sources, Marscher (1999) suggested that the flow in the sub-pc environment of these sources has already decelerated substantially. Additional support for slow flows in sub-pc scales comes from Jorstad et al. (2001) that showed that in several cases VLBI components in BLs move with $\beta_{app} \sim 1-2$. That low jet velocities at pc scales are real and not the result of projection effects is supported by the observation of subluminal velocities at the jet of the FR I galaxy 3C 270 jets, which are thought to be at large angle to the observer's line of sight (Piner et al. 2001).

3. Decelerating flows and UC emission

Motivated by the above issues, we propose that in the high energy emitting region of the TeV BLs the plasma flow is relativistic and *decelerating* (a similar proposal was advanced to unify the broadband properties of the hot spots of FR II radio galaxies and quasars (Georganopoulos & Kazanas 2003)). Our proposed scheme for the BL flows involves the injection of a power law electron distribution at the base of a relativistic flow which decelerates while at the same time the electron distribution cools radiatively. The highest synchrotron frequencies originate at fast base of the flow where the electrons are more energetic. As both the flow velocity and electron energy drop with radius, the locally emitted synchrotron spectrum shifts to lower energies while its beaming pattern becomes wider. At small angles the observed spectrum is dominated by emission from the higher Γ base of flow, where the most energetic electrons reside. At larger angles this emission from the inner, fast flow section is beamed away from the observer and the major contribution to the spectrum comes from its slower parts which contain less energetic electrons, leading to softer spectra.

The inverse Compton emission of such a flow behaves in a more involved way: Electrons will upscatter the locally produced synchrotron seed photons, giving rise to a local SSC emission with $\delta-$dependence similar to that of synchrotron. However, the electrons of a given radius scatter will also those synchrotron photons produced downstream in the flow. The energy density of the latter, will appear Doppler boosted in the fast (upstream) part of the flow by $\sim \Gamma_{rel}^2$ (Dermer 1995), where Γ_{rel} is the relative Lorentz factor between the fast and slow part of the flow. With their maximum energy being lower (because of cooling) and their energy density amplified they contribute to the IC emission at energies higher than expected on the basis of uniform velocity models without the need of invoking as large Doppler factors. The beaming pattern of this UC radiation is also intermediate between the synchrotron/SSC pattern of $\delta^{2+\alpha}$ and the external Compton pattern (EC) of $\delta^{3+2\alpha}$ (Dermer 1995; Georganopoulos, Kirk & Mastichiadis 2001), where α is the spectral index of the radiation. To demonstrate this consider a two-zone flow, a fast part with Lorentz factor Γ_1 followed by a slower part with Lorentz factor Γ_2. Consider also an observer located at an angle θ such that the Doppler factors of the two zones are δ_1, δ_2. The beaming pattern of the UC radiation in the frame of the slow part of the flow will be $\delta_{1,2}^{3+2\alpha}$, where $\delta_{1,2}$ is the Doppler factor of the fast flow in the frame of the slow flow. To convert this beaming pattern to the observer's frame we need to boost it by $\delta_2^{2+\alpha}$. The beaming pattern is then written as $\delta_{1,2}^{3+2\alpha}\,\delta_2^{2+\alpha}$. To write $\delta_{1,2}$ as a function of δ_1, δ_2, we note that a photon emitted in the fast part of the flow is seen by the observed boosted in energy by a factor δ_1. The same boosting can take place is two stages: first going to the frame of the slow flow by being boosted by $\delta_{1,2}$ and then going to the observer's frame by being boosted by δ_2. Because the final photon energy in the observer's frame does not depend on the intermediate transformations, $\delta_{1,2} = \delta_1/\delta_2$.

The beaming pattern of UC scattering is therefore $\delta_1^{3+2\alpha}/\delta_2^{1+\alpha}$. Note that, as expected, for $\delta_1 = \delta_2$, we recover the beaming pattern of SSC, while for $\delta_2 = 1$, that of EC radiation.

To demonstrate the relevance of decelerating flows in TeV blazars, we developed a simple model, based on an one dimensional kinematic flow description. An electron distribution $n(\gamma) \propto \gamma^{-2}$ is injected at the base of a decelerating relativistic flow with velocity profile $\Gamma(z) = \Gamma_o(z/z_o)^{-2}$. Electrons cool radiatively as they propagate downstream. We calculate their radiative losses along the flow and also their energy distribution as a function of z. We then calculate the synchrotron emissivity along z and, performing the necessary beaming transformations and $z-$integration, the volume integrated synchrotron emission as a function of observing angle θ. Using the synchrotron emissivity as a function of z we calculate the SSC and UC emissivities as a function of z, θ. A final integral over z then provides the volume integrated Compton emissivity as a function of θ. In fig. 1 we plot the SED for a deceleratring flow for two different observing angles. Note that at $\theta = 3°$ this model achieves a peak energy for the high energy component at $\sim$ 10 TeV, using a modest Lorentz factor of $\Gamma_1 = 15$. Note also the stronger angle dependence of emission from the inner fast part of the flow which produces the highest frequencies in each spectral component. Finally, note that, in contrast to single velocity homogeneous SSC models, the Compton component is more sensitive to orientation than synchrotron, as expected if UC scattering dominates the $\sim$ TeV observed luminosity.

We now turn to the problem of the unification of BLs with FR I sources. Chiaberge et al. (2000) and Trussoni et al. (2003) compared a sample of FR I nuclei to BLs of similar extended radio power, which is believed to be non-beamed, and therefore orientation independent. They found that de-beaming the BL emission under the uniform velocity assumption by changing the observer's angle from $\theta = 1/\Gamma \simeq 4°$ to $60°$ leads to fluxes far smaller than those of FR Is. In particular the average BL to FR I nucleus luminosity ratio at radio, optical and X-ray bands was found to be: $\log(L_{BL}/L_{FR\,I})_R \approx 2.4$, $\log(L_{BL}/L_{FR\,I})_{opt} \approx 3.9$, $\log(L_{BL}/L_{FR\,I})_X \approx 3.5$. In fig. 2 we plot as vertical bars the luminosity separation of BLs and FR Is according to Chiaberge et al. (2000) and Trussoni et al. (2003). We also plot the SED of a decelerating flow with physical parameters similar to that in fig. 1, but with smaller value for γ_{max} to produce SED synchrotron peaks similar to those of the intermediate BLs that correspond in extended radio power to the FR Is (Chiaberge et al. 2000; Trussoni et al. 2003). As can be seen, the luminosity change of the model SED at $\theta = 60°$ (FR I) and $\theta = 1/\Gamma$ (BL) reproduce relatively well the observed luminosity range.

4. Discussion

The need for additional seed photons in modeling the $\sim$ few TeV peak emission of the TeV blazars drives homogeneous SSC models to $\delta \gtrsim 50$, values in conflict with the presumed unification between FR I's and BLs. The problem of the missing seed photons can be resolved if one considers a relativistic flow decelerating from $\Gamma_1 \sim 15$ down to $\Gamma_2 \sim$ a few: in this case UC emission produces spectra that can easily provide the observed de-absorbed E_p without the need to invoke values of δ greater than $\delta \simeq 15$. Such decelerating flows are consistent with the low, possibly subluminal, speeds observed in the sub-pc scale jets of MKN 421 and MKN 501 without unreasonable alingment requirements (for $\Gamma_2 = 4$ and $\beta_{app} = 1$ the corresponding value of the observing angle is $\theta = 2°$). It also resolves the problem of FR I – BL unification, which fails for flows with constant Lorentz factors even as low as $\Gamma \sim 10$.

The spatial separation of different frequencies seen in Fig. 1 has interesting consequences for the expected variability. In homogeneous SSC models a variation of the number of the injected electrons produces a linear response in the synchrotron flux and a quadratic one in the SSC flux. This is because both the number of the electrons and the synchrotron energy density increase linerarly and the SSC flux increases quadratically because is proportional to their product. For decelerating flows, fast variations (faster than the light crossing time of the separation between the X-ray emitting region and the downstream region responsible for most of the synchrotron seed photons used to produce the TeV emission) should result to approximately linear variations of the TeV relative to the X-ray flux. This is because the freshly injected high energy electrons UC scatter mostly synchrotron photons produced downstream before the injection, and therefore contribute an undisturbed photon energy density.

A physically plausible scenario for the flows we consider may be that suggested by Marscher (1999), according to which the energy dissipated at the shock is converted into a non-thermal electron component, whose radiative losses lead to the deceleration of the relativistic flow. In this case the deceleration length scale would be approximately equal to that of radiative losses, an assumption we have employed in our calculations. A similar scenario has been proposed for the hot spots of large scale jets, and it seems possible that relativistic and decelerating flows exist in different astrophysical environments which exhibit similar characteristics, and in particular a stronger that anticipated high energy emission due to UC scattering.

REFERENCES

Aharonian, F. et al. 2002, A&A, 384, L23

Chiaberge, M. Celotti, A., Capetti, A & Ghisellini, G. 2000, A&A, 358, 104

Coppi, P. S. 1992, MNRAS, 258, 657

Dermer, C. D. 1995, ApJ, 446, L63

Edwards, P. G. & Piner, B. G. 2002, ApJ, 579, L67

Gould, J. & Schréder, G. 1966, Phys. Rev. Lett., 16, 252

Georganopoulos, M., Kirk, J. G. & Mastichiadis, A. 2001, ApJ, 561, 111

Georganopoulos, M., Kazanas, D. 2003, ApJ, 589, L5

Hardcastle, M. J., Worrall, D. M., Birkinshaw, M., & Canosa, C. M. 2003, MNRAS, 338, 176

de Jager, O. C., & Stecker, F. W. 2002, ApJ, 566, 738

Jorstad, S. G., Marscher, A. P., Mattox, J. R., Wehrle, A. E., Bloom, S. D. & Yurchenko, A. V. 2001, ApJS, 134, 181

Krawczynski, H., Coppi, P. S., & Aharonian, F. 2002, MNRAS, 336, 721

Laing, R. A., Parma, P., de Ruitter, H. R. & Fanti, R. 1999, MNRAS, 306, 513

Malkan, M. A., Stecker, F. W. 2000, ApJ, 555, 641

Marscher, A. P. 1999, Astrop. Phys., 11, 19

Mastichiadis, A. & Kirk, J. G. 1997, A&A, 320, 19

Nikisov, A. I. 1962, Sov. JETP 14, 393

Piner, B. G., Unwin, S. C., Wehrle, A. E., Edwards, P. G., Fey, A. L.& Kingham, K. A. 1999, ApJ, 525, 176

Piner, B. G., Jones, D. L. & Wehrle, A. E. 2001, AJ, 122, 2954

Primack, J. R., Somerville, R. S., Bullock, J. S. & Devriendt, J. E. G. 2001, in High Energy Gamma-Ray Astronomy: International Symposium, AIP Conf. Proc., 558, 463

Salamon, M. H. & Stecker, F. W. 1998, ApJ, 493, 547

Stecker, F.W., De Jager, O. C., Salamon, M. H. 1992, ApJ, 390, L49

Trussoni, E., Capetti, A., Celotti, A., Chiaberdge, M. & Feretti, L. 2003, A&A, 403, 889

Urry, C. M., & Padovani, P. 1991, ApJ, 371, 60

Urry, C. M., & Padovani, P. 1995, PASP, 107, 803

This preprint was prepared with the AAS LaTeX macros v5.0.

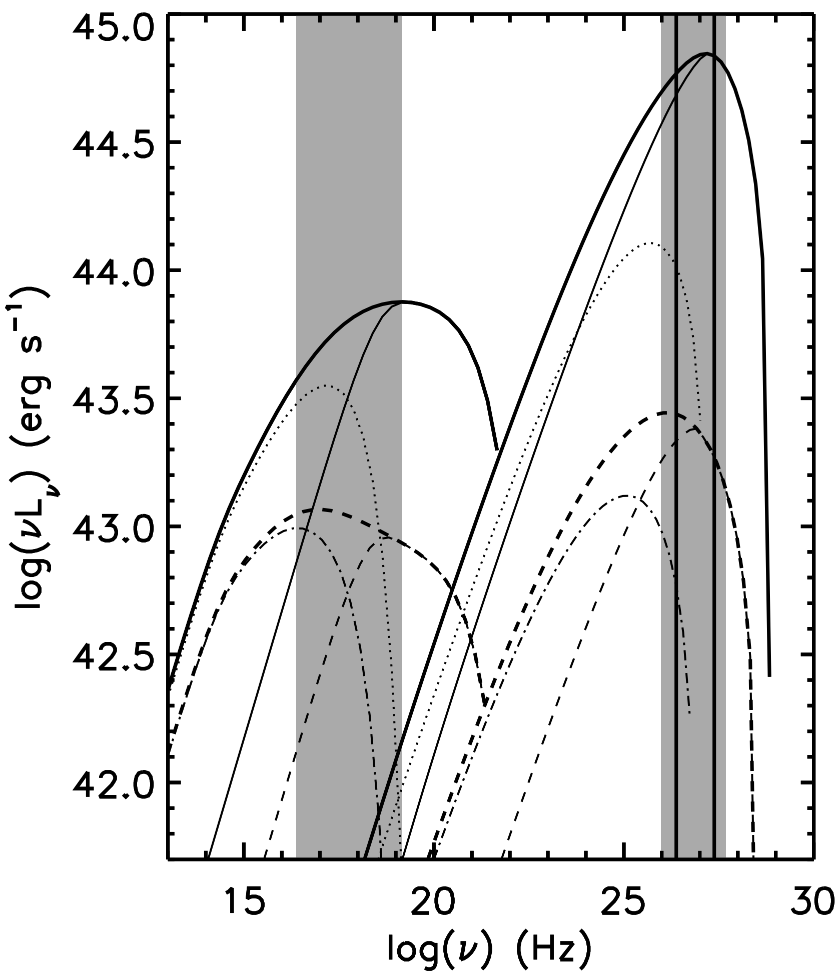

Fig. 1.— The synchrotron and inverse Compton emission from a decelerating relativistic flow under $\theta = 3^o$ (thick solid line) and $\theta = 6^o$ (thick broken line) observing angles. The flow decelerates from $\Gamma_1 = 15$ to $\Gamma_2 = 4$ within a length $Z = 2 \times 10^{16}$ cm. The radius of the cylindrical flow is set to $R = Z = 2 \times 10^{16}$ cm. A power law electron energy distribution, $n(\gamma) \propto \gamma^{-2}$, $\gamma \leq 3 \times 10^7$ is injected at the base of the flow with a magnetic field $B = 0.1$ G, half of the equipartition value. The thin solid and broken lines correspond to the emission due to the fast inner 10% of the flow, while the dotted and dash-dotted thin lines correspond to the rest of the flow. The shaded areas correspond approximately to the energy range of X-ray and TeV telescopes and the two vertical solid lines energies to 1 and 10 TeV.

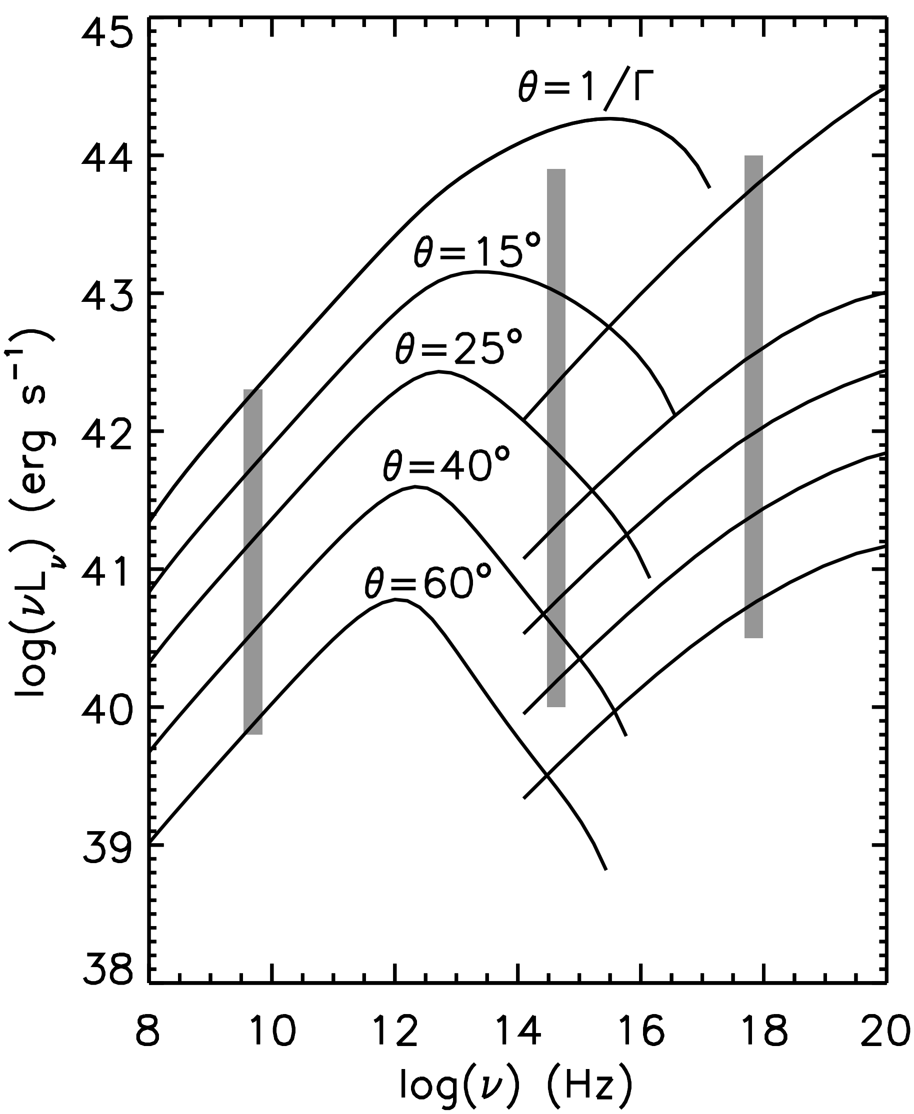

Fig. 2.— The SED of a decelerating flow for a range of observing angles. The physical parameters are similar to the one shown in fig. 1, except from the maximum electron energy which has been reduced to $\gamma_{max} = 2 \times 10^5$. The shaded bars corresponds to the average luminosity difference in radio, optical and X-rays, between the samples of Bls and FR I radio galaxies studied by Trussoni et al. (2003).